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ORIGINAL ARTICLE

Combining mechanical control of couch grass (*Elymus repens* L.) with reduced tillage in early autumn and cover crops to decrease nitrogen and phosphorus leaching

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Abstract Methods for control of couch grass (*Elymus repens* L.) with reduced tillage and cover crops to achieve low risk of nitrogen (N) and phosphorus (P) leaching were investigated. Treatments with reduced post-harvest tillage (one or two passes with duckfoot cultivator), hoeing between rows in combination with a cover crop, and a cover crop mown twice during autumn were compared with treatments with conventional disc cultivation and the control without tillage or cover crop. The study was conducted on a sandy soil in Sweden with measurements of N and P leaching. A 2-year experimental protocol was used, repeated twice. Treatments were implemented in the first year, and effects on couch grass (shoot density, shoot and rhizome biomass) were measured during autumn and in the second year. Significant effects of a single duckfoot cultivation and cover crop strategies were observed on couch grass shoot density in autumn but persistent effects were not verified. In conclusion, a single cultivation after harvest instead of repeated reduced the risk of N leaching and a cover crop in combination with hoeing or mowing effectively reduced it. Repeated cultivations resulted in mean annual N leaching of 26 kg N ha^{-1} compared with 20 kg in the treatment with one cultivation, 17 kg in the control, 16 and 12 kg in cover crop treatments with mowing and hoeing, respectively. The P leaching was small (0.04–0.09 P ha^{-1} year^{-1}), but there were indications of increased P drainage water concentrations in the treatment with a cover crop which was mown.

Keywords Leaching · Nutrients · *Elymus repens* · Weed control · Competition · Reduced tillage

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Introduction

Soil tillage is one of the key components of crop production. It prepares the soil for the crop and is an important part of the control of both annual and perennial weeds. However, soil tillage is time- and energy-consuming and is one of the main factors affecting the risk of nitrogen (N) leaching (Catt et al. 2000). Worldwide, there is increasing interest among farmers in reduced tillage and no-till systems, which in addition to reduced workloads and N leaching also reduce CO_2 emissions (Koga et al. 2003; Stajnko et al. 2009). On the other hand, these systems carry the risk of over-reliance on herbicides and the potential environmental problems associated with herbicide use, e.g. contamination of groundwater and surface water. Thus, for effective weed control there is a trade-off between the environmental goals of minimising nutrient leaching and reducing the use of herbicides.

For the control of problematic perennial weeds, such as couch grass (*Elymus repens* L.) that commonly exists and causes great yield losses in a variety of crops in the northern and southern temperate zones, there is often a choice between intensive use of non-selective herbicides and autumn tillage. In conventional agriculture, the most common control method for couch grass is application of glyphosate [*N*-(phosphonomethyl)glycine], a broad-spectrum herbicide. Due to its wide use, glyphosate has been frequently detected in European groundwater and surface water monitoring programmes (Horth and Blackmore 2009). To mitigate the increasing herbicide resistance in weeds as well as environmental pollution, a EU directive has set requirements for reduced dependence and sustainable use of pesticides (2009/128/EC, European Commission 2015). In organic farming, herbicides are prohibited and couch grass is mainly controlled by intensive tillage, often in the form of repeated stubble cultivations during autumn, followed by ploughing. This method works by fragmenting the rhizomes, starving them of energy and preventing any build-up of new energy reserves (Håkansson 1969). However, it requires tillage being performed from crop harvest in late summer until late autumn, which may increase risk of nutrient leaching losses in northern Europe, where there is often high water surplus during this time period. Consequently, alternative cost effective weed control methods, i.e. methods that could effectively control couch grass and other perennial weeds but depend less on herbicides and have minimum increase in N leaching, are needed for both organic and conventional agriculture.

The cropping systems with the least N leaching in the temperate zone are those with no or limited soil tillage during autumn (Mitchell et al. 2000), preferably in combination with a growing crop (Hansen and Djurhuus 1997). Soil tillage disrupts the vegetation cover and incorporates crop residues into the soil. Therefore, tillage in early autumn often results in accumulation of soil mineral N due to reduced plant uptake and increased N mineralisation (Lindén and Wallgren 1993; Känkenen et al. 1998; Catt et al. 2000), which in turn increases the risk of N leaching. Myrbeck et al. (2012) concluded that the time of first tillage, which interrupts plant N uptake, is more important for mineral N accumulation in the soil during autumn than tillage depth. However, tillage depth and intensity will decide the degree of soil aggregate disruption and crop residue incorporation, which may affect N mineralisation. Laboratory studies have shown that the rate of respiration increases with the amount of energy applied to the soil (Dexter et al. 2000; Watts et al. 2000). Several studies have confirmed that increased tillage intensity during autumn increases soil mineral N accumulation and the risk of N leaching (Goss et al. 1993; Stenberg et al. 1999; Catt et al. 2000), while this was not confirmed by other studies (Aronsson and Stenberg 2010; Hansen et al. 2010).

Undersowing cover crops (e.g. grasses or grass/-clover mixtures) in cereal crops have proven to be very efficient in reducing N leaching, and is a technique widely used within mitigation programmes in northern Europe for reduced nutrient load from arable land. Undersown cover crops combine the effect of delayed or omitted tillage in autumn with active N uptake (Hansen and Djurhuus 1997; Torstensson and Aronsson 2000; Thorup-Kristensen et al. 2003). Omitted tillage, in combination with cover crops, may significantly lower N leaching, but restricts the possibilities to perform active weed control and could therefore result in increased weed populations (Myrbeck and Stenberg 2014). It is difficult to achieve a cover crop that is vigorous enough to compete effectively with couch grass (Ringselle et al. 2015), but without reducing yield of the main crop (e.g. Cussans 1972; Bergkvist et al. 2010). To enhance weed control, cover crops can be combined with mechanical treatments, which are less intensive than stubble cultivation, e.g. mowing or row hoeing. Repeated mowing or hoeing during autumn would potentially have a similar effect as repeated stubble cultivation, where the weed is triggered to reshoot and where the stored resources are gradually drained (Håkansson 1969). However, unlike stubble cultivation, mowing or row hoeing causes less damage to cover crops, giving them a better chance to compete with couch grass and reduce N leaching.

For phosphorus (P), the use of cover crops and consequently reduced tillage might have a twofold effect. On one hand, cover crops may reduce particulate P losses due to reduced soil erosion during autumn and winter (Uusi-Kämppä 2008), compared to soil which is tilled during autumn (Lundekvam and Skøien 1998). On the other hand, it may increase dissolved P losses through surface runoff or leaching due to P release from crop materials incorporated (Neumann et al. 2011) or left on the soil surface, exposed to freezing over winter (Bechmann et al. 2005; Sturite et al. 2007; Liu et al. 2013).

The main objective of this study was to evaluate methods for control of couch grass that are sustainable with respect to water quality issues, i.e. minimizing use of herbicides and leaching of N without increasing P losses. Different treatments with reduced tillage (i.e. reduced tillage depth and/or reduced amounts of operations) in combination with or without cover crops (hoeing between rows or mowing) were tested during 2 years in a field leaching experimental facility, with measurements of soil mineral N, leaching of N and P and couch grass abundance.

The specific hypotheses tested were that (1) undersown cover crops, in combination with mowing or row hoeing, reduce couch grass biomass compared to control treatment and reduce N leaching compared to treatments with stubble cultivations after harvest, (2) shallow stubble cultivation with duckfoot shares, once or twice, is as effective in the control of couch grass as repeated stubble cultivation with a disc cultivator, but causes less N leaching and (3) cover crops do not affect P leaching, compared to the treatments without cover crops.

Materials and methods

Field site

The study was conducted on a sandy soil at Lilla Böslid experimental farm in south-west Sweden (56°35′N, 12°56′E). This region has a mean annual temperature of 7.2 °C and mean annual precipitation of 803 mm (Halmstad 1961–1990). The soil in the area consists of sand deposits covering a clay layer, and is commonly tile-drained because of high groundwater levels. Drainage commonly occurs during the period from October to April. The topsoil (0–30 cm depth) consists of 7 % clay, 5 % silt, 84 % sand and 4 % organic matter. The subsoil (30–90 cm depth) is dominated by sand (1 % clay, 98 % sand). The experimental field consists of 36 separately tile-drained plots, each 320 m^2, in three blocks. The experimental drainage system was constructed in 2002. The tile drains are at 0.9 m depth, 6 m apart. All plots are equipped for continuous measurements of drainage water flow and flow-proportional water sampling.

Experimental setup

The study was conducted using a 2-year experimental protocol (year 1 and year 2 are hereafter referred to as Y1 and Y2). This was repeated over two experimental rounds (ER1 and ER2) running in 2011–2012 and 2012–2013, respectively (Fig. 1). For each ER, 18 tile-drained plots (16 m × 20 m) were used, with 6 treatments and 3 replicates in a randomised complete block design. Experimental treatments were implemented in Y1, after harvest of spring barley (*Hordeum vulgare*, L.) in August. The residual treatment effects on couch grass and yield of subsequent oats were measured in oats (*Avena sativa,* L.) sown in spring Y2. Leaching of N and P was measured from May Y1 until April Y2. The experiment was terminated 3 weeks after harvest of oats in Y2.

Four couch grass control methods were applied during autumn Y1 (Table 1): (a) one pass with a duckfoot cultivator at 0.07 m depth (abbreviated 1×Duck), (b) two passes with a duckfoot cultivator (2×Duck), (c) row hoeing twice in combination with a cover crop (Hoe/CC) and (d) mowing twice in combination with a cover crop (Cut/CC). They were compared with (1) a control treatment (Control) with no stubble cultivation or cover crop and (2) a conventional method with two stubble cultivations (Disc) by discs to 0.10–0.12 m depth in August–September. The use of a duckfoot cultivator was assumed to result in less N mineralisation than disc cultivation due to less soil disturbance, but still to provide acceptable control of couch grass, since the majority of the rhizomes are located in the upper 0–0.075 m of soil (Chandler et al. 1994). The method with hoeing between the rows might be especially suitable for organic farming where a wider distance between rows is commonly used to enable weed hoeing in the growing crop. Soil was tilled with duckfoot cultivator after harvest of barley in 1×Duck, and in 2×Duck tillage was applied again 4–5 weeks later (2–4 leaf stage of couch grass). In the Disc

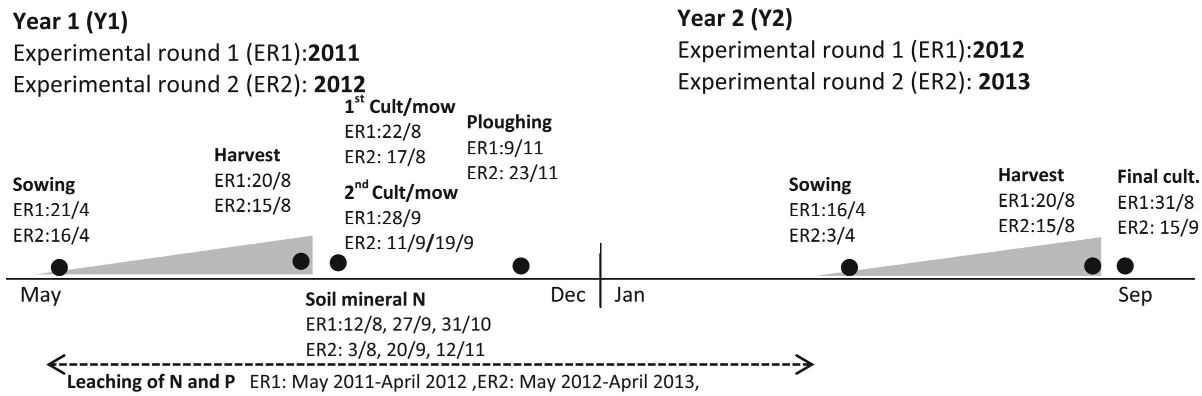


Fig. 1 Description of the 2-year experiment which was repeated in two experimental rounds (2011–2012 and 2012–2013, respectively). Treatments were implemented in year 1, and dates for the management practices during the two ERs are given. *Black circles* indicate when couch grass was graded or sampled

Table 1 Experimental treatments applied during late summer and autumn in year 1 (Fig. 1), i.e. the first of two experimental years, which was repeated in two experimental rounds (2011–2012 and 2012–2013, respectively)

	Cultivation/mowing	Cover crop	Row spacing (m)
Control	–	–	0.12
Disc	Disc, twice	–	0.12
1×Duck	Duckfoot, once	–	0.12
2×Duck	Duckfoot, twice	–	0.12
Hoe/CC	Duckfoot hoe, twice	Grass/clover	0.24
Cut/CC	Mowing, twice	Grass/clover	0.12

All treatments were ploughed in November (0.20 m depth)

treatment, two cultivations were applied on the same dates as for 2×Duck.

Dates of the management practices relating to the experimental treatments are given in Fig. 1. In the Hoe/CC treatment, a crop row spacing of 0.24 m was used in Y1 (compared with 0.12 m in the other treatments) in combination with a grass/clover cover crop undersown in the rows of the main crop. Inter-row hoeing was performed at the same time as in 2×Duck, i.e. just after harvest and 4–5 weeks later. In ER1, inter-row hoeing was also carried out in May in the growing crop in order to control annual weeds, which was not considered necessary in ER2 due to lower weed density. Thus, two possible weed control methods were combined, i.e. cover crop competition and mechanical disturbance. In Cut/CC, an undersown cover crop was used which was cut twice (at approximately the same time as the tillage events in 2×Duck and Hoe/CC). Thus, cover crop competition and mechanical disturbance were combined as in Hoe/CC, but using other mechanisms of interference. The cover crops in Hoe/CC and Cut/CC consisted of red clover (*Trifolium pratense* L., var. Ares, 5 kg ha^{-1}) and perennial ryegrass (*Lolium perenne* L., var. Prana, 10 kg ha^{-1}), which were undersown on the same day as the main crop. Crops were fertilised with 90 kg N ha^{-1}, 15 kg P ha^{-1} and 53 kg K ha^{-1}. The seed rate for spring barley in year 1 was 190 kg ha^{-1}. In treatment Hoe/CC (0.24 m row spacing), the seed rate was reduced by 10 % in ER1, but not in ER2. Dicot weeds were controlled by applying Amidosulfuron in May in all plots, in both experimental rounds. All plots were ploughed in November Y1. In Y2 all plots were stubble-cultivated after harvest.

Grading, sampling and analysis of crops and couch grass

Three methods were used to measure the abundance of couch grass; grading of shoot density, cutting of aboveground biomass and rhizome sampling. Due to considerable variation in weed infestation intensity over the field (according to visual observations <1–40 % cover), initial shoot density and biomass samples taken pre-treatment were used as covariates, as described in the "Statistics" section. Shoot density grading was performed four times in Y1 (2 weeks after emergence of the main crop, before harvest, 20 days after harvest, and in November before ploughing) and three times in Y2 (2 weeks after emergence of the main crop, before harvest and 20 days after harvest). This was done using a 'grading fork' consisting of a frame 36 cm long with four 28 cm long tines, creating three inter-tine areas of 333 cm^2 each (Ringselle et al. 2015). Occurrence/non-occurrence of at least one shoot in each inter-tine area was recorded, giving a value between 0 and 3. The average score from ten random estimates along two transects in each plot was used as a measure of couch grass density.

Couch grass shoot and rhizome biomass were collected before harvest both in Y1 (start of tillage treatments) and in Y2. Shoot biomass was cut from three 0.25 m^2 squares in each plot. The samples were dried at 105 °C for 24 h and weighed. Rhizome biomass was collected using a golf hole drill with 0.105 m diameter and 0.21 m depth (0.0086 m^2 and 0.0018 m^3). Eight samples were collected in ER1 and ER2Y1, but 16 in ER2Y2. The samples were sieved and washed, dried at 105 °C for 24 h and weighed.

The main crops (barley or oats) were harvested with a combine harvester in two strips per plot, resulting in two samples which were dried at 50 °C for 24 h and weighed. To determine biomass and N content of the cover crops, aboveground plant parts were cut (about 0.01 m above the soil surface) from nine randomly selected 0.25 m^2 squares in each plot on two occasions during autumn; about 1 month after harvest (18 September) and about 2–3 weeks before ploughing (25 October and 1 November, respectively). For the Cut/CC treatment this corresponded to about 1 month after the first mowing and 1–1.5 months after the second mowing. These samples were then pooled into three subsamples for each plot, which were dried, weighed and analysed for N by combustion on an elemental analyser (Leco CNS-2000, Leco Corp., St Joseph, MI, USA; Kirsten and Hesselius 1983).

Sampling and analysis of drainage water and soil

The treatment effects on accumulation of soil mineral N (SMN) were studied during the first autumn (Y1). Leaching of N and P was measured from May in Y1 over winter until April in Y2, i.e. during May 2011 to April 2012 (ER1) and during May 2012 to April 2013 (ER2), Fig. 1. Drainage water flow from each plot was measured with tipping buckets connected to a data-logger, which stored daily drainage volumes. Flow-proportional water samples (15 mL per occasion) were taken using a peristaltic pump after every 0.2 mm discharge. Samples were collected in individual polyethylene bottles for each plot, which were emptied every 2 weeks during drainage periods for analysis of total N. To determine total N concentration, a combustion catalytic oxidation method was used where all N was converted to nitrous oxide before analysis (Shimadzu TOC-VCPH+TNM-1) according to the relevant European standard (SS-EN 12260-1). The total P concentration was determined on unfiltered samples according to methods issued by the International Standard Organization (ISO 15681-12003), where all P is oxidised with $K_2S_2O_8$ to PO_4-P, which is analysed photometrically.

Daily N and P leaching loads were calculated by multiplying the daily drainage volume by the N and P concentrations in the water sample correspondingly collected during the 2-week period. The daily N and P loads were accumulated to monthly leaching loads and then divided by monthly drainage amounts to give mean monthly concentrations. Drainage and leaching loads were summarised for four periods; main crop growing period (May–August), autumn until ploughing (September–November), winter (December–January) and spring (February–April).

To measure the accumulation of SMN during autumn, soil samples for determination of nitrate–N and ammonium-N were taken before harvest (approximately at yellow ripeness of the crop), in late September and in late October or early November, Fig. 1. From the layers 0–0.3, 0.3–0.6, and 0.6–0.9 m depth, 10–20 samples were collected with a tube drill in each plot. The samples were mixed by layers and then analysed after extraction with 2 M KCl. The concentration of nitrate-N, including nitrite-N, was analysed by flow injection analysis according to the colorimetric Cd reduction method (APHA 1985). Concentrations of ammonium-N were determined using a combined flow injector gas diffusion method (Tecator 1984) in which the extract is injected into a carrier stream and mixed with 0.1 M NaOH solution. The analytical values were converted to kg N ha^{-1}

using dry bulk density and water content values specific for each layer.

Statistics

Cereal grain yield, couch grass rhizome and shoot biomass were analysed as g m^{-2} using a linear mixed model consisting of the main effects (ER, treatment) and their interactions as fixed variables, and block as a random variable (ER × block). Couch grass shoot density was analysed with the addition of plot (ER × plot) as a random variable. The addition of the random plot variable enabled two gradients per plot to be used in the analysis, without treating them as replicates. This basic model was used to analyse the starting conditions in Y1 (spring and harvest measurements). Post-treatment data were analysed with the addition of a covariate, the corresponding data generated at harvest Y1, with the exception of spring Y2, which was analysed using spring Y1 data as covariate. Effects prior to sampling Y1, whether from random unknown factors or effects of the cover crop during summer, were therefore adjusted for by the covariate. Couch grass data and cereal grain yield were analysed in JMP 9.0.2 (SAS Institute Inc.).

Soil mineral N, drainage amounts and N and P leaching were analysed using a linear mixed model. The SMN analysis included four main effects (ER, treatment, depth, sampling time) and the leaching analyses three main effects (ER, treatment, period). The main effects and their interactions were analysed as fixed factors and block as a random variable (ER × block). Since they were not independent measures, depth, sampling time and period were all treated as repeated measures. The unstructured type was used, since it gave the lowest AIC of the different covariance structure types. SMN and leaching analyses were performed in SAS 9.3 (SAS Institute Inc.). Tukey's HSD tests were used for all post-analysis comparisons.

Results

Soil mineral N in autumn

Tillage and cover crop treatments affected SMN dynamics in the soil during autumn and thereby also N leaching. Temperature conditions during autumn Y1 were quite similar in the two ERs. Mean monthly air temperature measured at the field site declined during the autumn, from 16–17 °C in August to 13–14 °C in September, 8–9 °C in October and 6–7 °C in November. Precipitation conditions varied substantially, where August was wet in ER1 (134 mm compared to 66 mm in ER2), while November was considerably wetter in ER2 (147 mm compared to 35 mm in ER1). Precipitation in September and October was similar, on average 124 and 85 mm in ER1 and ER2, respectively. Repeated cultivation by disc or duckfoot cultivator resulted in a considerable increase in SMN in both topsoil and subsoil in September and November compared with the control and the cover crop treatments (Fig. 2). One early duckfoot cultivation also increased SMN in September, but it had declined by November. Use of a cover crop did not significantly reduce total SMN amounts compared with the control, but showed a clear ability to reduce the risk of N leaching by preventing accumulation of SMN below 0.6 m depth, especially in ER1 (not shown). The interactions treatment × depth and treatments × ER were not significant, because the trends in the effect of treatment were similar in both ERs and at all depths (Table 2). Thus, the overall pattern of the treatment effects on SMN was the same for both experimental rounds and for all depths.

Cover crop biomass during autumn

Cover crops were undersown with the same mixture of grass and clover in both ERs (10 kg ha^{-1} ryegrass and 5 kg ha^{-1} red clover), but the final composition at sampling in autumn differed, i.e. no clover in ER1 and 7–40 % clover in ER2. Where the cover crop was sown with double row spacing with hoeing (Hoe/CC), the total amount of aboveground living plant material at sampling in October–November amounted to 780 and 870 kg ha^{-1} in ER1 and ER2, respectively. The corresponding N content of the cover crop shoots was 15–17 kg ha^{-1}. Similar values have been found in previous studies of cover crop growth on this site (Aronsson et al. 2011). Where the cover crop was mown twice (Cut/CC), total cover crop shoot biomass was somewhat larger than in Hoe/CC. In total, approximately 850 and 1000 kg ha^{-1} of cover crop plant material (19 and 24 kg N ha^{-1}) were collected on the two sampling occasions in ER1 and ER2,

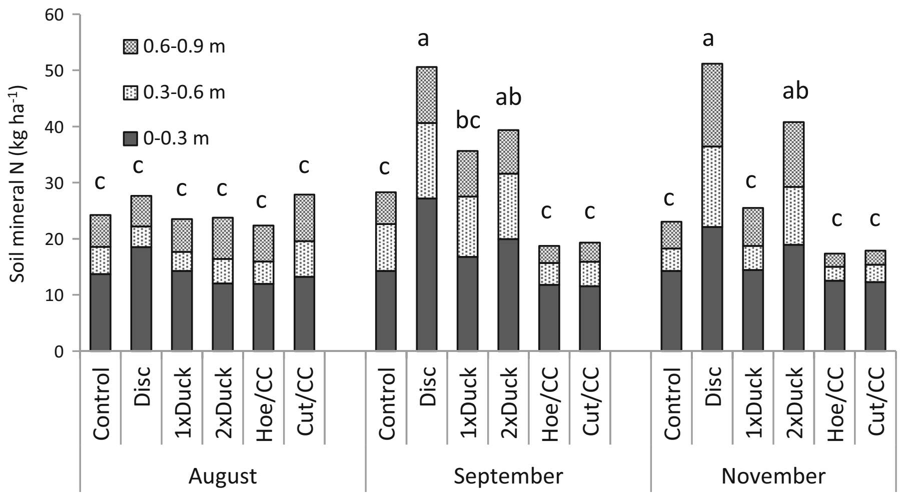


Fig. 2 Average values for ER1 and ER2 of soil mineral N content in different soil layers (0–0.3, 0.3–0.6, and 0.6–0.9 m depth) during autumn Y1. Significant differences between treatments (0–0.9 m depth) are indicated by *different letters*

Table 2 Analysis of variance table of the statistical model used to calculate statistical significance for differences in soil mineral nitrogen at different times and soil depths

	Df	F	*P*
Depth	2	193	<0.0001
Time	2	8.35	0.0011
Time × depth	4	20.9	<0.0001
Experimental round (ER)	1	1.25	0.3
Depth × ER	2	7.82	0.0014
Time × ER	2	8.99	0.0007
Time × depth × ER	4	5.63	0.0008
Treatment	5	21.7	<0.0001
Depth × treat	10	1.18	0.3
Time × treat	10	6.42	<0.0001
Time × depth × treat	20	2.72	0.0009
Treat × ER	5	0.36	0.9
Depth × treat × ER	10	1.08	0.4
Time × treat × ER	10	2.51	0.02
Time × depth × treat × ER	20	3.49	<0.0001

respectively, where the cover crop was mown once between these occasions.

Nitrogen and phosphorus leaching

Although the total amounts of N leaching differed between ER1 and ER2, the differences between the treatments were consistent (Fig. 3; Table 3). This was mainly due to differences of N concentrations in drainage water, while differences in drainage water amounts between treatments were negligible. However, there were large variations in drainage between periods and between ERs due to varying precipitation conditions. The precipitation was considerably higher during ER1 (1207 mm) than during ER2 (666 mm) and mean annual drainage (May 1–April 30) was 506 and 283 mm year^{-1} for ER1 and ER2, respectively. During both ERs, drainage constituted 42 % of the precipitation.

Drainage in period 1 (growing season) occurred only in ER1 and the total N concentrations in drainage water were low (3–6 mg L^{-1}) in all treatments (Fig. 4), until December (period 3), when they increased in some treatments. In contrast, tillage in August ER2 immediately resulted in markedly increased concentrations in period 2, as soon as drainage started in August. The drainage water N concentrations in the treatments with two cultivations remained high over winter in both ERs. The differences between the treatments (Table 3; Fig. 4) were also in agreement with the differences found in SMN (Table 2; Fig. 2). However, N leaching varied over the year and there were also interactions between treatments and periods. The largest N leaching losses occurred during period 3 and 4 in ER1 (Dec–Jan and Feb–Apr, respectively) and period 2 and 3 in ER2 (Sep–Nov and Dec–Jan, respectively) (Fig. 3), when treatment differences also appeared. The cover crop treatments had significantly less N leaching than the other treatments, except for the control, while the treatments with two cultivations had significantly larger N leaching than all others. The cumulated N

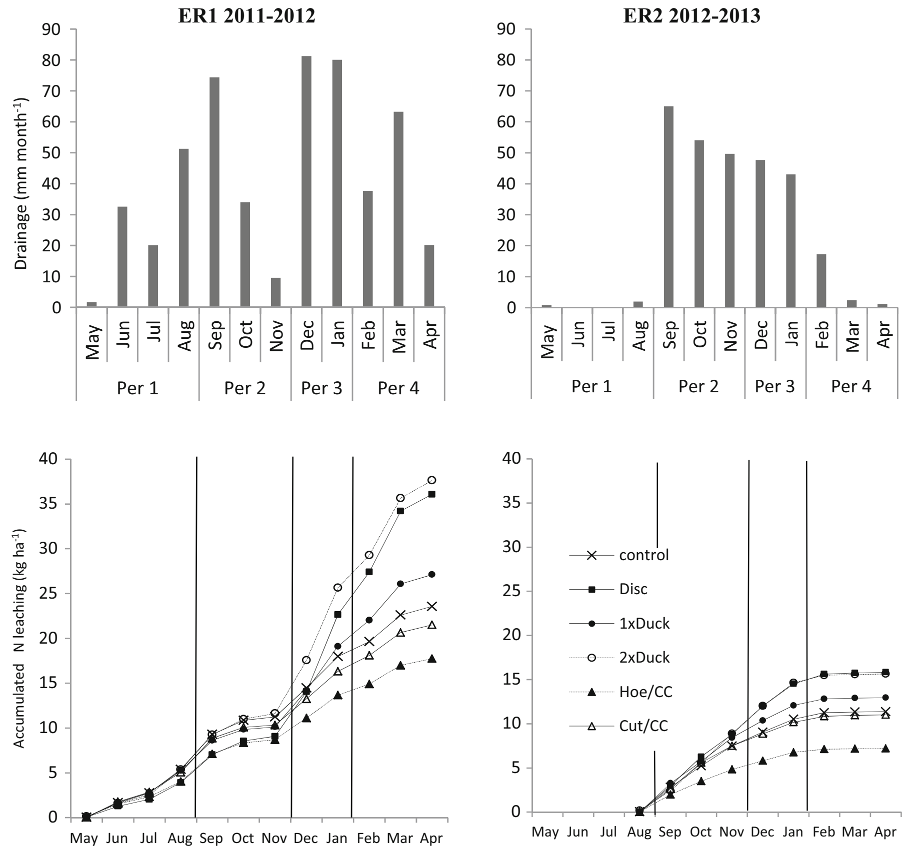


Fig. 3 Mean monthly drainage amounts and cumulated monthly leaching of total N. Per 1: May–Aug, Per 2: Sep–Nov, Per 3: Dec–Jan, Per 4: Feb–Apr

Table 3 Analysis of variance table of the statistical model used to calculate statistical significance for differences in drainage amounts, N and P concentrations and leaching during different periods of the year

	Df	Drainage		N-concentration		N-leaching		P-concentration		P-leaching	
		F	*P*	F	*P*	F	*P*	F	*P*	F	*P*
Period	3	140	<0.0001	11	0.0001	171	<0.0001	23	<0.0001	79	<0.0001
Treatment	5	1	0.6	14	<0.0001	5	0.0035	2	0.15	1	0.5
P × T	15	1	0.2	6	<0.0001	13	<0.0001	2	0.025	2	0.055
ER	1	80	<0.0001	6	0.063	23	0.0015	0	0.9	32	0.0013
P × ER	3	72	<0.0001	12	<0.0001	63	<0.0001	31	<0.0001	42	<0.0001
T × ER	5	2	0.2	1	0.5	1	0.4	1	0.7	1	0.6
P × T × ER	15	2	0.13	1	0.3	3	0.0031	2	0.13	2	0.072

ER experimental round, *P* period, *T* treatment

leaching was, on average, 27 kg N ha^{-1} year^{-1} in ER1 and 12 kg N ha^{-1} year^{-1} ER2. The range for individual treatments was 18–38 kg N ha^{-1} year^{-1} in ER1 and 7–16 kg N ha^{-1} year^{-1} in ER2.

In contrast to N, P concentrations in drainage water and leaching loads were not apparently affected by tillage treatments. Overall, P leaching was low in both experimental rounds (0.04–0.09 kg ha^{-1} year^{-1}). In ER1, total P concentrations declined from September until April in all treatments and were lowest during period 4 (Feb–Apr), while in ER2 they increased over time and reached highest values during winter, especially in the two treatments with cover crops (Fig. 4).

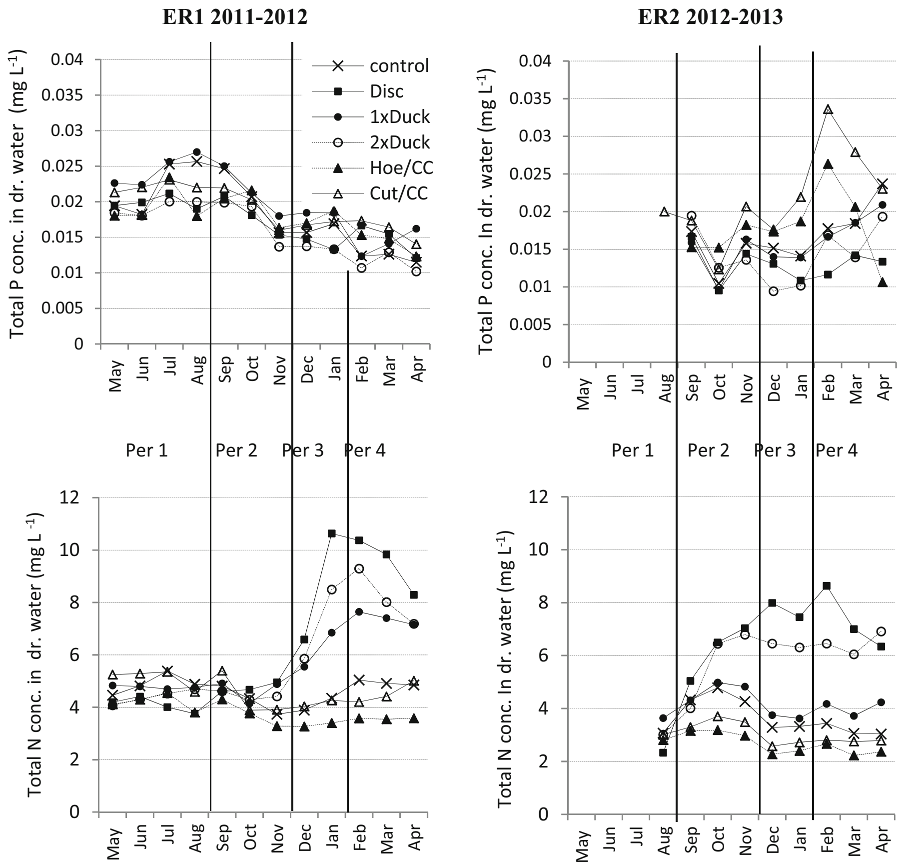


Fig. 4 Mean monthly concentrations of total P and total N in drainage water. Per 1: May–Aug, per 2: Sep–Nov, per 3: Dec–Jan, per 4: Feb–Apr

Where the cover crop was mown twice, annual P leaching was higher than in the other treatments (0.07 compared with 0.03–0.04 kg ha^{-1} $year^{-1}$), but there were large variations between plots and the differences in concentrations and leached amounts were not significant (Table 3). The high concentrations in ER2 during period 4 were accompanied by low drainage and thus did not result in increased losses of P, but were rather an indication of P transport.

Couch grass control

There were differences in couch grass shoot density in autumn Y1, in spring Y2 and at harvest in Y2, depending on the tillage and cover crop strategies (Table 4). The cover crop treatments and the treatment with a single duckfoot cultivation had the lowest couch grass shoot density in early autumn Y1 (not shown), and with cover crops the density was still lowest in late autumn Y1 (Fig. 5a). For the treatment Hoe/CC, which was more effective than the Cut/CC treatment, the effect persisted in spring Y2 (Fig. 5b), but was not detectable in the grading at harvest Y2 (Fig. 5c). Measurements of shoot biomass and rhizome dry weight at harvest in Y2 could not confirm any control effect, even if the average differences were great (Table 4), due to considerable variation. The tendencies for differences indicate possible effects of duckfoot cultivation and cover crop treatments (Table 4; Fig. 5d, e). Grain yields in Y2 were not significantly affected by the different treatments (Table 4).

Discussion

The results presented here show that potential exists for developing strategies that combine tillage and cover crops for couch grass control with considerably less N leaching than with traditional soil cultivation methods. In one treatment, we were able to execute weed hoeing while still maintaining a viable cover

Table 4 Analysis of variance table of the statistical model used to calculate statistical significance for shoot density, shoot biomass and rhizome biomass of couch grass and grain yield of main crop during year 2 (Y2)

	Df	Shoot density early autumn Y1 *p*	Shoot density late autumn Y1 *p*	Rhizome biomass late autumn Y1 *p*	Shoot density spring Y2 *p*	Shoot density harvest Y2 *p*	Shoot biomass harvest Y2 *p*	Rhizome biomass harvest Y2 *p*	Grain yield Y2 *p*	Shoot density early autumn Y2 *p*
ER	1	0.023	0.6	–	0.00	0.1	0.044	0.4	0.0002	0.26
Treatment	5	<0.0001	<0.0001	0.6	0.020	0.0079	0.056	0.15	0.11	0.033
ER × T	5	0.2	<0.0001	–	0.483	0.073	0.053	0.14	0.094	0.19
Covariate	1	0.5	<0.0001	0.057	0.0038	<0.0001	0.0001	0.0003	0.0011	0.25

The covariate is the shoot density, shoot or rhizome biomass at harvest Y1 except shoot density Y2 where the covariate is the shoot density at spring Y1

ER experimental round, *P* period, *T* treatment

crop, thereby reducing the N leaching. A single shallow cultivation and use of a cover crop in combination with hoeing or mowing both resulted in less N leaching than repeated cultivation treatments. There were also indications that the tillage and cover crop treatments (combined with hoeing or mowing) had some controlling effects on couch grass (confirming hypotheses 1 and 2), although effects found in autumn Y1 were not verified with statistical significance at harvest in Y2. Further research is needed to verify any effects and if promising, to develop recommendations for practical use. There was no significant effect of cover crops on P leaching which supported hypothesis 3. However, increased drainage water P concentrations during winter in ER2 in the treatment where the cover crop was mown indicate that this needs to be further investigated.

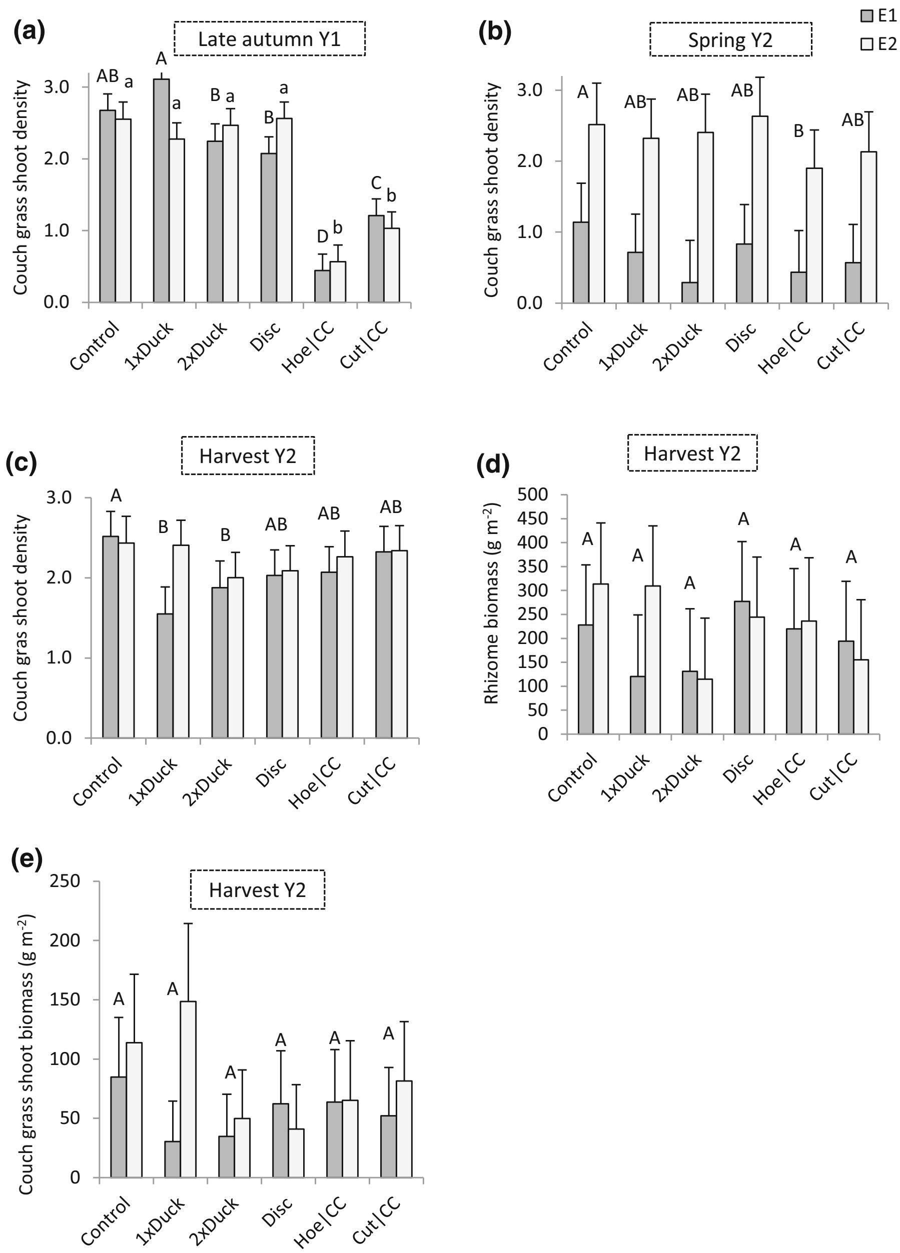
Cover crop and N leaching

The N leaching reduction effect of the cover crop was not studied separately from cutting and cultivation. Hoeing twice with a duckfoot cultivator between the rows probably increased N mineralisation during autumn, as indicated in the treatment with repeated duckfoot cultivation without a cover crop (Fig. 2). Similarly, mowing without harvesting the cut material must have increased N release, which might have contributed to larger amounts of mineral N in the topsoil than if it had not been cut. However, some of the lost N from the cut material was probably recycled into the growing cover crop. Despite hoeing or mowing, the cover crops effectively withstood the transport of leachable N downwards. Nitrogen leaching was considerably less than from cultivated treatments, although not significantly different from the control without stubble cultivation. It is well known that cover crops reduce N leaching compared with soils untilled until late in autumn (Thomsen et al. 1993; Hansen and Djurhuus 1997). The small effects of the cover crop treatments compared with the control were probably because the positive effects by cover crops were counteracted by hoeing and mowing, but weeds growing in the control (not measured) might also have contributed to less N leaching due to N uptake.

Tillage and N leaching

These results confirm findings in several previous studies (e.g. Stenberg et al. 1999; Catt et al. 2000; Mitchell et al. 2000), that repeated disc cultivation during autumn constitutes a clear risk of N leaching. Consequently, it is one of the reasons why mechanical control of weeds during autumn is questionable with respect to water quality issues. Repeated disc or duckfoot cultivations resulted in mean annual N leaching of 26 kg N ha^{-1}, compared with 17 kg N ha^{-1} in the control. There were also clear indications that one duckfoot cultivation resulted in less accumulation of mineral N in the soil in November and less mean annual N leaching (20 kg N ha^{-1}) than repeated cultivations. Thus, the results from autumn Y1 indicated that one optimised cultivation

Fig. 5 Couch grass shoot density **a** in late autumn year 1 (Y1) and **b** in spring Y2, **c** at harvest Y2, **d** rhizome biomass at harvest Y2 and **e** couch grass shoot biomass at harvest Y2. *Error bars* indicate 95 % confidence intervals. *Letters* show results of a Tukey HSD test at α = 0.05. Analyses with significant interactions between treatment and ER (Table 4) are presented with separate Tukey tests, differentiated by *upper* versus *lower case*. Analyses without significant interactions display a single Tukey test (*upper case*)



with a duckfoot cultivator may be a compromise if needed for couch grass control, with only a slightly increased risk of N leaching. However, any effect on couch grass during Y2 could not be verified with statistical significance. This study did not show that duckfooot cultivation twice (0.07 m depth) resulted in less N leaching than disc cultivation twice (0.1 m depth), which was assumed in hypothesis 2. One reason could be that the difference in tillage depth was small. However, this supports findings by Myrbeck et al. (2012), who also found small differences between tillage methods in autumn, i.e. stubble cultivation (0.08 m depth) and mouldboard ploughing.

Phosphorus leaching

The P losses were very small from the study soil, less than 0.1 kg ha^{-1}, and thus any influence of different treatments on P losses was of no practical importance. This is probably due to the combination of the texture and high P sorption of this unstructured sandy soil used, where percolating water is evenly distributed and where the soil matrix acts like a filter for P when water is transported downwards (Andersson et al. 2013). Nitrate-N, on the other hand, is transported efficiently due to lack of sorption (Aronsson et al. 2011). Supporting our initial hypothesis, we found similar P leaching in treatments with and without cover crops. However, in ER2, but not in ER1, measurements indicated higher ($p = 0.15$) concentrations of total P in drainage water from Cut/CC and Hoe/CC than from other treatments, especially for Cut/CC (mown cover crop) in period 3. Differences between ERs are likely due to differing winter conditions. The P content of the cut material in Cut/CC was not measured, but according to Aronsson et al. (2011) the P content of the cover crop aboveground biomass could be 2–4 kg P ha^{-1} (0.25–0.37 % of aboveground plant biomass). During ER1 there was 1 month (January 20–February 17) when the cover crop was exposed to freezing (not shown). During ER2, the winter was more severe with a total of 83 days distributed over four frost periods during 4 months (December–March). This may be the reason why ER2 tended to have higher drainage water P concentrations than ER1, as Bechmann et al. (2005) and Liu et al. (2014) reported that repeated freezing–thawing events can increase the release of water-soluble P from plant material. Due to the high retention of P by the soil, P release from cover crops was not a major concern for the study soil, but for soils with fast transport pathways in macropores (e.g. clayey soils) or with surface runoff, increased availability of dissolved P from plant material would probably constitute a considerable risk of increased P losses.

Couch grass control

Ringselle et al. (2015) concluded that repeated mowing during autumn can reduce couch grass rhizome biomass, but a low-yielding cover crop (30–60 g m^{-2} in October) will only reduce autumn shoot biomass, and not the rhizome biomass. The rhizome biomass can be viewed as accumulated biomass reflecting the growing conditions during the whole season and perhaps previous seasons, while the shoot biomass adjusts faster to the prevailing conditions. In the present study, the cover crop biomass measured in Hoe/CC in late autumn amounted to 80–90 g m^{-2}. This was close to the cover crop biomass in studies reporting a reduction in couch grass rhizome biomass due to cover crop competition (Cussans 1972; Bergkvist et al. 2010). Because of the relatively dense cover crop, the trend of reduced rhizome weight in treatments with cover crops could be due to a combined effect of the cover crop and the repeated cutting or hoeing for control of the couch grass. The growth and N uptake by the cover crop in this experiment was considerable and enough for SMN depletion during autumn. Therefore N competition should have been severe, but might have been introduced too late to substantially reduce rhizome biomass. The N content of aboveground biomass of the uncut cover crop in late autumn was 14–18 kg ha^{-2}, which was within the expected range for conditions in the Nordic countries (Hansen and Djurhuus 1997; Thomsen et al. 1993; Torstensson and Aronsson 2000).

Surprisingly, the conventional treatment with repeated disc cultivations did not reduce the shoot density or rhizome weight of couch grass compared with the control. For the conditions at this specific site (e.g. soil type and weather conditions), the duckfoot cultivator seemed to be more efficient for couch grass control than the disc cultivator. The soil was an unstructured sandy soil, and it is possible that on such soils shallow couch grass rhizomes can be more efficiently pulled up onto the soil surface by duckfoot shares than on more clayey soils. Fragmentation of rhizomes, which is the main function of disc cultivation, may be more important on clayey soils.

The controlling effect of the treatments on couch grass was small in this study, and could be regarded more or less a positive side-effect of reduced N leaching. An important remaining question is to what extent the methods investigated here can be improved in order to make them efficient for couch grass control. Higher cover crop density during autumn would be desirable, but this must be balanced against the risk of reduction of the main crop yield if the cover crop is undersown and also against possible negative impacts of inter-row hoeing on grain yield.

Conclusions

Although the couch grass control effect was weak, the results from this study are interesting for further development of control measures which combine reduced tillage and cover crops to achieve a decreased risk of N leaching.

Treatments with a single shallow duckfoot cultivation after harvest of main crop or with undersown cover crops for competition with weeds and for N uptake during autumn, indicated that it may be possible to achieve the goals of both couch grass control and a reduced risk of N leaching. The most promising treatment was combining a growing cover crop in autumn with repeated hoeing between the rows, since, the cover crop indicated effects on couch grass, managed to inhibit accumulation of soil mineral N and N leaching and did not increase the risk of P leaching.

The combination of a cover crop and mowing also reduced N leaching and indicated an effect on couch grass. Phosphorus leaching was not significantly affected, but there were indications of increased P concentrations in drainage when a cover crop was mown and the plant material left in the field. This indicates that the release of P from cover crop plant material may constitute an increased risk of losses over winter.

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